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Removing Trihalomethanes from Drinking Water
An Overview of Treatment Techniques

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Removing Trihalomethanes from Drinking Water

An overview of treatment techniques

by James M. Symons, Alan A. Stevens, Robert M. Clark, Edwin E. Geldreich, O. Thomas Love, Jr. and Jack DeMarco

In 1974, researchers, both in this country[1] and in The Netherlands[2] discovered that chloroform, bromodichloromethane, dibromochloromethane and bromoform, were formed during the chlorination step in drinking water treatment. Nationwide surveys showed that this reaction occurred to some extent in every drinking water treatment plant where free chlorine was being used for disinfection. As a result of these findings, an intensive research program was begun here and abroad to study all aspects of this emerging problem. Six years later, although research on some aspects was still continuing, sufficient new information was available to warrant compiling these data into a single research report,[3] summarized in this article, as an update of the June, 1976 "Interim Treatment Guide for Controlling Chloroform and Other Trihalomethanes."

Section 1401 (1)(D) of the Safe Drinking Water Act, PL 93-523, states that "the term 'primary drinking water regulation' means a regulation which contains criteria and procedures to assure a supply of drinking water which dependably complies with such maximum contaminant levels..." and Section 1412 (a)(2) states that "National interim primary drinking water regulations promulgated under paragraph (a)(1) shall protect health to the extent feasible, using technology, treatment techniques, and other means, which the Administrator determines are generally available (taking costs into consideration)..." Thus, for any regulated contaminant, a "Treatment Techniques" document must accompany the establishment of a "Maximum Contaminant Level" (MCL) to provide compliance guidance. The research report[3] satisfies the treatment document requirement for the Trihalomethane Regulation promulgated November 29, 1979,[4] and is a companion to the "Manual of Treatment Techniques for Meeting the Interim Primary Drinking Water Regulations."[5]

For completeness, the report covers several topics related to trihalomethanes in drinking water in summary fashion. It is a practical text offering guidance to water utilities, consulting engineers, Primacy Agencies and many others.

Health Effects

The finding in 1976 by the National Cancer Institute that chloroform was a carcinogen to rats and mice, and the positive associations between drinking water quality and some human cancer sites in several of 18 retrospective epidemiological studies led the U.S. Environmental Protection Agency (U.S.EPA) to suspect chloroform and other trihalomethanes of being human carcinogens. Under the Safe Drinking Water Act provisions, this presumed health effect necessitated regulating the concentration of trihalomethanes in drinking water.

Trihalomethane Regulation

On November 29, 1979, the U.S.EPA promulgated an amendment to the National Interim Primary Drinking Water Regulations establishing a Maximum Contaminant Level (MCL) of 0.10 mg/l for "Total Trihalomethanes," which is the arithmetic sum of the concentrations of chloroform ($CHCl_3$), bromodichloromethane ($CHBrCl_2$), dibromochloromethane ($CHBr_2Cl$), and bromoform ($CHBr_3$). That regulation applies to community water systems that add a disinfectant in the treatment process and serve a population of greater than 10,000 customers. Compliance with the regulation must be accomplished within 2 years for community systems serving greater than 75,000 customers and within 4 years for community systems serving between 10,000 and 75,000 customers.[4,5]

Measurement

The Trihalomethane Regulation[4] states that samples must be collected headspace-free and should be analyzed within 14 days by one of two gas chromatographic procedures, either the purge-and-trap technique or the liquid-liquid extraction technique. Further, these analyses must be performed by certified laboratories.

Mechanism of Formation

Trihalomethanes are primarily formed by the reaction of free chlorine with humic materials, for example, humic and fulvic acids, called trihalomethane precursors. The reaction is not instantaneous, but takes place over a period ranging from 1 or 2 hours to several days. It is influenced by temperature, pH, precursor type and concentration, bromide concentration, disinfectant residual type, and possibly disinfectant residual concentration.

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16. ABSTRACT

In 1974 trihalomethanes (chloroform, bromodichloromethane, dibromochloromethane and bromoform) were discovered to be formed during the disinfection step of drinking water if free chlorine was the disinfectant. This, coupled with the perceived hazard to the consumer's health, led the U.S. Environmental Protection Agency to amend the National Interim Primary Drinking Water Regulations to include a maximum contaminant level of 0.10 mg/L tor total trihalomethanes.

For trihalomethane removal, aeration - either by diffused-air or with towers - and adsorption - either by powdered activated carbon or granular activated carbon - is effective. The major disadvantage of this approach is that trihalomethane precursors are not removed by aeration. For trihalomethane precursor control, effective processes are: 1) oxidation by ozone or chlorine dioxide; 2) clarificationby coagulation, settling and filtration, precipitative softening, or direct filtration; or 3) adsorption by powdered activated carbon or granular activated carbon. In addition, some modest removal or destruction of trihalomethane precursors can be achieved by oxidation with potassium permanganate lowering the pH, or moving the point of chlorination to the clarified water. Lowering of trihalomethane precursor concentrations has the additional advantage of

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reducing overall disinfectant demand, thereby reducing the possibility of the formation of all disinfection byproducts.

Neither chlorine dioxide, nor ozone, nor chloramines produce trihalomethanes at significant concentrations when used alone as disinfectants. Furthermore, the cost of any of these unit processes is very low. The major disadvantage of using alternate disinfectants for trihalomethane control relates to the lack of any precursor removal.

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Table 1
Summary of Salient Features of Practical and Effective Processes for Controlling Trihalomethanes in Drinking Water

Treatment	Precursor	Trihalomethanes	Other By-Products	Disinfection	Representative Estimated Rounded Cost for 100 mgd in ¢/1000 gal 20 percent Removal	50 percent Removal	80 percent Removal	Remarks
Ozone oxidation	Good to very good destruction is technically feasible. The apparent concentration increases at low doses. High doses and long contact times are required for good destruction, complete destruction is difficult.	No effect by ozone, some incidental gas stripping.	Some are formed, but they will not contain chlorine, unless free chlorination or chlorine dioxide is employed. Bromine-containing THM *may* not be formed on later chlorination.	Excellent, but no residual is created. Organisms may re-grow in the distribution system.	Caddo Lake Water, Precursor Removal 2 mg/l 1.8	20 mg/l 7.9 —with contact chambers—	50 mg/l 15	Slightly better at high pH.
Chlorine dioxide oxidation	Good destruction is technically feasible, but complete destruction was not achieved.	No effect	Some are formed by the process and some will contain halogen.	Good and provides a residual. Slightly more effective at higher pH.	Ohio River Water, Precursor Removal Not determined	8 mg/l 12 w/o contact chambers	Not achieved	Residual oxidant should be limited to 0.5 mg/l because of health effect.
Potassium permanganate oxidation	Fair destruction is technically feasible, but complete destruction was not achieved.	No effect	Some are formed by the process and some will contain halogen, if free chlorine or chlorine dioxide is used.	Poor, a disinfectant must be used.	Ohio River Water, Precursor Removal 10 mg/l for 10 hr 10 without contact chamber	Not achieved	Not achieved	Pink water with overdose, better at high pH.
Lowering pH	Fair decline of TermTHM concentration is technically feasible. Affects the rate of reaction between free chlorine and precursor, thereby lowering resulting THM concentration.	No effect	None formed by the process, but some formed during final disinfection.	Free chlorine is more effective at lower pH.	Daytona Beach, FL, Precursor Removal 0.9 pH unit 19 percent* Equiv. of 2 mg/l H_2SO_4/0.12	Not achieved	Not achieved	May cause some corrosion problems.
Diffused air aeration	No effect and THM will form if free chlorine is used.	Good to very good removal is technically feasible, but bromine-containing THMs are harder to remove than chloroform. High air to water ratios are difficult to achieve.	None are known to be formed by the process but some are still formed during disinfection. By-products will contain halogen if free chlorine or chlorine dioxide is used.	A disinfectant is required.	Cincinnati, OH Tap Water, THM Removal A/W** = 2/1 1.8	A/W = 8/1 6.2	A/W = 20/1 14	Influent air can be cleaned. Possible air pollution problems. Removes regulated contaminant. Some removal of SOCs†† and T&O† compounds.
Tower aeration	No effect and THM will form if free chlorine is used.	Good to very good removal is feasible, but bromine-containing THM's are harder to remove. High air to water ratio can be achieved.	None known to be formed by the process, but some are still formed during disinfection. By-products will contain halogen if free chlorine or chlorine dioxide is used.	A disinfectant is required.	North Miami Beach, FL, THM Removal Not determined	A/W = 4/1 2.1	A/W = 32/1 2.9	Difficult to clean air, may entrain particulates. Possible air pollution problems. Removes regulated contaminant. May have to protect from freezing. Some removal of SOCs†† and T&O† compounds.

Powdered activated carbon adsorption	Good to very good removal is feasible. Removal is influenced by influent concentration and the loading is proportional to the influent concentration.	Good to very good removal is feasible. Bromine-containing THMs are better adsorbed than chloroform. Removal is influenced by influent concentration and the loading is proportional to the influent concentration.	None are formed by the process. Some removal of those coming to the process and less reformation as related to TOC reduction. Will contain halogen if chlorine or chlorine dioxide is used.	Removes chlorine, so must post-disinfect. Some reduction in disinfectant demand.	Louisville, KY Tap Water—THM Removal 10 mg/l 2.8 Ohio River Water—Precursor Removal 9.5 mg/l Starting at 1 umol/l 2.8	50 mg/l 13 43 mg/l Starting at 1 umol/l 11	150 mg/l 39 222 mg/l Starting at 1 umol/l 57	Some removal of SOCs[††] and T&O[†] compounds. No desorption with decreasing concentration because PAC only used once. Sludge disposal a problem.
Granular activated carbon adsorption	Good to very good removal technically feasible. Removal is nearly complete when adsorbent is fresh, then breakthrough *foward* exhaustion begins. Complete exhaustion generally does not occur, however. Loading is proportional to influent concentration and desorption may occur when the influent concentration declines.	Good to very good removal is technically feasible. Removal is nearly complete when adsorbent is fresh but then breakthrough *to* exhaustion occurs. Bromine-containing THM adsorbed better than chloroform. Loading is proportional to influent concentration and desorption will occur if the influent concentration drops.	None formed by the process and some can be removed. Because of good TOC removal, fewer are formed during disinfection.	Chlorine removed, so post-disinfection required. Disinfectant demand is lower when TOC is removed.	Huntington, WV—THM Removal 7 min. EBCT[***] 7 wks. react. Sand replacem. 6.0 Huntington, WV—Precursor Removal 7 min. EBCT[***] 5.5 wks react. Sand replacem. 7.1	7 min. EBCT[***] 4 wks. react. Sand replacem. 9.0 7 min. EBCT[***] 3 wks. react. Sand replacem. 11	7 min. EBCT[***] 2 wks. react. Sand replacem. 16 7 min. EBCT[***] 1 wk react. Sand replacem. 28	SOCs[††] and T&O[†] compounds also removed. Requires reactivation or replacement. Complete removal does not last long. Possible corrosion problems if effluent TOC[†††] concentration near zero.
Clarification by coagulation, sedimentation, filtration	Good removal is feasible. If reaction with free chlorine is fast, delaying chlorination to after clarification will permit more removal. More removal will occur at lower pH but the reaction between free chlorine and precursor will be slower.	No effect.	None formed by the process and some may be removed. Because of TOC removal, fewer are formed later during disinfection. Some will contain halogen if free chlorine or chlorine dioxide is used.	Disinfectant demand lower if disinfection is delayed.	Precursor Removal Wheeling, WV 16 percent* Lime= 16 mg/l Ferric sulfate= 8 mg/l 15	Fox Chapel, PA 4 percent* Alum= 27 mg/l Lime= 17 mg/l 15	Not achieved	Sludge disposal problem. Iron salts may be somewhat better than alum.
Clarification by precipitative softening	Good removal is technically feasible. The faster reaction rate between free chlorine and precursor at higher pH should result in additional benefit by delaying chlorination.		None formed by the process. Because of TOC removal, fewer are formed during disinfection. Some will contain halogen if free chlorine or chlorine dioxide is used.	Effectiveness of free chlorine reduced at higher pH, Disinfectant demand will be lower if disinfection delayed.	Precursor Removal Jefferson Parish, LA 16-25 percent* Lime= 60 mg/l Cationic polymer= 4 mg/l 22	Daytona Beach, FL 41 percent* Lime= 225 mg/l Alum= 25 mg/l Polymer= 0.1 mg/l 21	Not achieved	Slude disposal a problem.
Clarification by direct filtration	Good removal is technically feasible. THM concentrations will be lower if chlorination is delayed to after the process.	No effect.	None formed by the process. Because of TOC removal, fewer are formed during disinfection. Some will contain halogen if free chlorine or chlorine dioxide is used.	Disinfectant demand lower if disinfection follows clarification.	Precursor Removal Not determined	Bridgeport, CT 36-54 percent* Alum= 21 mg/l Polymer= 0.1 mg/l 10	Not achieved	Little sludge produced. May require polymers.

* Actual percent removal at that location.
** A/W = Air to Water Ratio (Volume/Volume).
† T&O = Taste and Odor.
†† SOC = Synthetic Organic Contaminants.
*** EBCT = Empty Bed Contact Time (Empty Bed volume divided by flow rate).
††† TOC = Total Organic Carbon.

Trihalomethanes are primarily formed by the reaction of free chlorine with humic materials, for example, humic and fulvic acids, called trihalomethane precursors.

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Treatment Evaluation

In order to properly evaluate any proposed trihalomethane control scheme, the behavior of three parameters must be well understood.[7] These are: (1) instantaneous trihalomethane concentration (InstTHM), or the trihalomethane concentration at the time a sample is collected; (2) terminal trihalomethane concentration (TermTHM), or the prediction of some future trihalomethane concentration determined by storing a chlorinated sample for a specified time period under conditions that are equivalent to those encountered in the treatment plant or distribution system under study;* and (3) the trihalomethane formation potential concentration (THMFP) or the measure of the trihalomethane precursors that will eventually react with free chlorine to produce trihalomethanes under the selected conditions, calculated as the arithmetic difference between the previously two defined parameters.

Treatment Techniques

The reaction for the formation of trihalomethanes is: Free Chlorine + Precursors (Humic Substances) + Bromide---> Trihalomethanes + Other By-Products and leads to three approaches for controlling the concentration of trihalomethanes in drinking water. Any process must be evaluated in terms of maintaining or improving bacteriological and overall chemical qualtiy. Thus, minimizing the potential for the formation of other disinfection by-products is prudent.

Trihalomethane Removal. Three unit processes were studied: oxidation, aeration, and adsorption. Each of these processes has advantages and disadvantages. Of the oxidation processes studied, only ozone combined with ultra-violet radiation was effective for trihalomethane destruction, but the possibility of undesirable oxidation by-products being formed during treatment cannot be neglected.

Aeration can be effective for trihalomethane removal and does not produce any by-products. Waters high in the bromine-containing trihalomethanes are difficult to treat by aeration, however, because these compounds have a less favorable Henry's Law Constant compared to chloroform, thereby lowering the efficiency of the process. Further, aeration as a treatment technique has the disadvantage of possibly creating an air pollution problem. Finally, if aeration is contemplated, design factors may have to include an enclosure or some protection from freezing in some climates and include techniques for avoiding entrainment of particulates.

Two adsorbents were studied: activated carbon and synthetic resins. Of the two, the synthetic resin Ambersorb XE-340† was the more effective for trihalomethanes. Both were much more effective for adsorbing the bromine-containing trihalomethanes than for chloroform; therefore, if these species dominate the trihalomethane mixture in a given location, adsorption might be the most effective approach. Both of the granular adsorbents studied have to be renewed when exhausted and will desorb previously adsorbed contaminants if the influent concentration declines. If powdered activated carbon is used, sludge disposal may be a problem, because adsorbent doses needed for effective treatment may be much higher than commonly used for taste and odor removal.

Trihalomethane Precursor Removal. Of the seven techniques studied (clarification, source control, aeration, oxidation, adsorption, biological degradation and lowering the pH) all but aeration had a significant effect on the trihalomethane precursor concentration. If its control is desired, the raw water source should be examined to determine if changes are possible that would result in a lower concentration of trihalomethane precursors.

Clarification has been shown to be effective for removal of some trihalomethane precursors. Existing plants should be examined to determine if their performance can be improved by changing the coagulant dose, type or both. Additionally, under certain circumstances, existing plants using source water chlorination may be modified easily by moving the point of chlorination downstream to further reduce trihalomethane concentrations. These circumstances can be judged a priori by determining the concentrations of trihalomethanes and trihalomethane precursors (InstTHM, TermTHM and THMFP) at various stages. Chances for successfully lowering trihalomethane precursor concentrations by moving the chlorination point are better if: (1) under routine operations *prior* to moving the point of chlorination, a high percentage of trihalomethane precursors is settled out during clarification and (2) under routine operation *prior* to moving the point of chlorination, a high percentage of trihalomethane precursors has reacted with free chlorine to form trihalomethanes during clarification.

Another possible alternative is to operate the treatment plant and the distribution system at a lower pH, if high pH is the current method of preventing corrosion, or to investigate the use of potassium permanganate. These techniques may be instituted with minor modifications of existing processes.

If these relatively simple approaches to trihalomethane precursor removal are not sufficiently effective to lower the average concentration of total trihalomethanes in the distribution system to meet the total trihalomethane Maximum Contaminant Level, the designer and operator may try other approaches, such as ozone or chlorine dioxide oxidation, or adsorption with powdered activated carbon (PAC) or granular activated carbon (GAC). Note, during oxidation by chlorine dioxide, both chlorite and chlorate may be formed. Because of concerns over toxicity,[8] the U.S.EPA has recommended that the sum of the residual concentrations of chlorine dioxide, chlorite, and chlorate in the drinking water should not exceed 0.5 mg/l.[4]

Of the alternative treatments noted above, granular activated carbon adsorption is initially the most effective for trihalomethane precursor removal. When fresh, this adsorbent is able to provide almost complete removal of these materials from water. At empty bed contact times (empty bed volume divided by flow rate) of 5 to 10 min., however, this excellent performance is not long-lasting.

Use of Alternative Disinfectants. Although none of the unit processes studied (ozonation, combined chlorination and treatment by chlorine dioxide) produce trihalomethanes, each disinfectant has specific advantages and disadvantages beyond the general disadvantage that they all form some organic by-products.[8] Ozone is an excellent biocide and the biocidal activity is not affected by the pH of the

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*This is not to be confused with U.S.EPA Method 510.1 "Maximum Trihalomethane Potential" that is appropriately used only in connection with the Trihalomethane Regulation[4] for certain groundwater evaluations.

†Mention of commercial products does not constitute endorsement by the U.S. Environmental Protection Agency.

water. Ozone does not produce a disinfectant residual, however, and if it were used alone, no biocidal agent would be present in the distribution system. More than 1,000 water treatment plants around the world generate ozone on-site, but the generation equipment is more elaborate than that required when free chlorine is used. Finally, reports have indicated that when ozone is used, organics in the water become more biodegradable, and this can result in higher microbiological activity in the distribution system.

Chloramines (combined chlorine residual) have the advantage of being easy to generate and feed and produce a persistent residual that can be maintained through the distribution system. Chloramines are weaker biocides and the biocidal action is reduced when the pH of the water is high because monochloramine formation is favored over dichloramine formation. Two reports in the literature document possible problems with chloramine toxicity.[9,10] Chloramines are currently undergoing carcinogenesis bioassay at the National Cancer Institute.

Chlorine dioxide has several advantages as an alternative disinfectant; it has good biocidal activity over the pH range usually occurring in water treatment, so it is applicable to most systems. It can be generated and fed readily, although care is needed to maintain a low concentration of chlorine. Also, it produces a residual that can persist through the distribution system. Lastly, chlorine dioxide does not react with ammonia. Therefore, the disinfectant demand for chlorine dioxide may be somewhat less than for free chlorine.

A major disadvantage of using chlorine dioxide as an alternative is the formation of chlorite and chlorate. Because of the potential toxicity[8] of chlorite and chlorate, the U.S.EPA has recommended in the Trihalomethane Regulation that the sum of the residual concentrations of chlorine dioxide, chlorite and chlorate be limited to 0.5 mg/l in drinking water.[4] The use of chlorine dioxide may be limited if this recommendation is adopted by Primacy States because many waters in the U.S. have disinfectant demands that would result in a total residual concentration exceeding 0.5 mg/l when adequate chlorine dioxide is applied to meet the demand.

Of the three approaches to trihalomethane control, the use of alternate disinfectants appears to be the most effective and the least costly. Theoretically, any utility, with any trihalomethane precursor concentration, could reduce its trihalomethane concentration to almost zero by the use of one of these three disinfectant alternatives to free chlorine. Furthermore, the cost of any of these unit processes, calculated either with or without contact chambers, is very low. Because of the cost advantage, a water utility requiring trihalomethane control probably would consider the use of alternate disinfectants as the first approach to meeting the Trihalomethane Regulation,[4] but the utility managers and their consultants should also consider the disadvantages[8-11] of this approach.

Alternatively, for the control of trihalomethanes by removal of trihalomethanes and trihalomethane precursors, **Table 1** (pages 52-53) compares the performance and cost of 11 currently available unit processes. The table also describes the behavior of these unit processes with respect to several common areas: the effect on trihalomethane precursor concentrations, the effect on trihalomethane concentrations, the formation of other by-products, the effect on disinfection, and the representative estimated costs.

Using data collected at specific utilities studied, these estimated costs were calculated for a single size of treatment plant, 100 mgd, at three levels of treatment success and were based on the cost of chemical dosages and of other operating parameters that achieved specified levels of treatment. These data should be used for comparison purposes of costs for equal treatment

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and should not be taken as universally applicable. Absolute effectiveness of unit processes and costs will vary among locations.

Maintaining Bacteriological Quality

Drinking water treatment modifications to reduce trihalomethane precursors must be applied cautiously with careful consideration to the changes that such alternatives may introduce in the microbial quality of drinking water produced in the plant and transmitted through the distribution network. In all of the many field studies examined during this research effort, no overt evidence of microbial deterioration in the finished water leaving the treatment plant occurred. In the trade-off to delay disinfection until near the final stages of the treatment process to obtain lower trihalomethane concentrations, however, some microbial migration deeper into the treatment train must be accepted. Therefore, greater reliance must be placed on final disinfection, with maintenance of a disinfectant residual in the distribution system to effectively counter low level coliform populations and pathogens that have survived earlier treatment.

Microbial penetration of the multiple barriers in drinking water treatment is more pronounced during abnormal pollution loads in the source water. Under these situations, normal microbial reductions in early phases of the treatment chain will not be adequate to suppress the residual bacterial population to low levels. This condition places a greater burden on the last in-plant treatment barrier, i.e., disinfection. Therefore, daily bacteriological monitoring of all in-plant processes is recommended during periods of warm water temperatures, abnormal increases in source water pollution, or both. This approach, as a companion to microbiological and disinfection residual monitoring in a distribution system, will ensure that high-quality water will continue to be distributed to the consumer.

Examples of Treatment Options

To assist water utility managers, consulting engineers and others in assessing treatment options, some treatment possibilities for four systems** will be discussed:

The alternative of using a disinfectant other than free chlorine will not be discussed because that application is relatively straightforward. The reader is reminded of the disadvantages, cited previously, to this approach.

Consideration of these examples focuses on trihalomethane and trihalomethane precursor removal options in an attempt to show how water utility managers, consulting engineers and others can determine treatment effectiveness and estimated treatment costs as a first step to selecting the most reasonable options for pilot study. Many other treatment options are possible and should be considered in an actual case. As noted in **Table 1**, (pages 52-53) each process has disadvantages, and, although they are not always mentioned, they must not be overlooked.

(1A) *10 mgd Groundwater Utility†† TTHM Concentration 2xMCL - 0.15 mg/l InstTTHM in Finished Water:* In the case of the smaller utility treating groundwater by chlorination only, with a relatively high InstTHM concentration (0.20 mg/l) in the distribution system, an approximate 50 percent decline in the trihalomethane concentration in the distribution system would be required so that the average concentration of trihalomethanes in samples collected throughout the distribution system would be less than 0.10 mg/l. Because much of the source water precursor has been converted into trihalomethanes prior to leaving the treatment plant in this example (i.e., the InstTTHM concentration in the finished water was 0.15 mg/l with an increase of 0.05 mg/l out in the distribution system) then aeration could be employed to remove these trihalomethanes. According to **Table 1**, a 20:1 air to water ratio for a diffused-air system, or a 32:1 air to water ratio for a tower aeration system achieved 80 percent removal of the InstTHM at one location. This would produce an expected average InstTTHM concentration of 0.03 mg/l leaving the plant (0.15 - [0.8][0.15]) = 0.03 and 0.08 mg/l (0.03 + 0.05) out in the distribution system, less than the trihalomethane MCL.[4] An estimated added cost for these two systems would be 14¢/1,000 gal* and 4.5¢/1,000 gal, respectively, neglecting the cost of treating the air (filtering, scrubbing and so forth).

(1B) *10 mgd Groundwater Utility - TTHM Concentration 2xMCL - 0.01 mg/l InstTTHM in Finished Water:* Because a high percentage of the source water trihalomethane precursor has not been converted into trihalomethanes by the time the water leaves the treatment plant, some trihalomethane precursor removal process must be

**The first three examples will be discussed for two different cases: (A) Where a large percentage of the possible trihalomethane production has occurred rapidly at the treatment plant and (B) where a large amount of the possible trihalomethane production occurs in the distribution system after the water has left the plant.

††For the purposes of these examples, these groundwater systems are assumed to have all the flow collected in one location.

*All costs are rounded to two significant figures.

employed. Because only chlorination facilities are available at this example site, a treatment scheme with a minimum of construction should be considered first. Two possibilities are: (1) direct filtration for trihalomethane precursor removal or (2) granular activated carbon adsorption without any prior sedimentation. Approximatley 50 percent removal of the trihalomethane precursor would be sufficient so that the average of the samples collected in the distribution system would be lower than 0.10 mg/l.

According to **Table 1**, (pages 52-53) a coagulant dose of 21 mg/l of alum and 0.1 mg/l of polymer produced approximately 50 percent precursor removal by direct filtration at one location. Note, the water being treated at this location was a low turbidity surface water, but for this example the groundwater was assumed to behave similarly. The estimated added cost of such a process would be 25¢/1,000 gal for this system.

Correspondingly, a granular activated carbon adsorber having a 7-min. EBCT with the activated carbon replaced or reactivated every three weeks would achieve 50 percent removal of trihalomethane precursor. On a throw-away basis, the added cost of such a process would be $1.30/1,000 gal. Using on-site reactivation, the added cost would be 16¢/1,000 gal.

(2A) *10 mgd Groundwater Utility - THM Concentration 1.2xMCL - 0.05 mg/l InstTHM in Finished Water:* For the second example, a 10 mgd treatment plant with a groundwater source and chlorination only, whose average InstTHM concentration in the distribution system was 0.12 mg/l, only about 10 percent of either trihalomethane or trihalomethane precursor concentrations would be needed to bring this water utility's drinking water into compliance. Therefore, because a significant portion of the source water trihalomethane precursor has been converted to InstTHM in the finshed water, aeration could be considered for the removal of trihalomethanes. If the InstTHM concentration in the finished water were about 0.05 mg/l, an aeration device producing 50 percent removal might be adequate. This could be done with an air to water ratio of 8:1 for diffused air and 4:1 for aeration towers (**Table 1**). The added cost for these two unit processes for this size treatment plant would be 6.9¢/1,000 gal and 3.4¢/1,000 gal, respectively, neglecting the cost of treating the air.

(2B) *10 mgd Groundwater Utility - THM Concentration 1.2xMCL - 0.01 mg/l InstTHM in Finished Water:* Because insufficient InstTHM is present in the finished water to make trihalomethane removal a useful option, about a 20 percent removal of trihalomethane precursor would be required. Either lowering the pH, treatment with potassium permanganate, or treatment with about 2 mg/l of chlorine dioxide (estimated) could provide 20 percent removal of precursor, according to **Table 1** (pages 52-53) using data from specific locations, and would only involve the construction of a contact basin and the use of chemical feeders. The added cost for these three unit processes would be: pH control, 0.8¢/1,000 gal;† potassium permanganate, 11¢/1,000 gal; and chlorine dioxide, 9.0¢/1,000 gal, respectively. Of course, if chlorine dioxide oxidation was considered as an alternative, investigations would have to include a determination of the production of the inorganic by-products chlorite and chlorate, to compare with the *recommended* limit for the total oxidants of 0.5 mg/l.

(3A) *100 mgd Surface Water Utility - THM Concentration 2xMCL - 0.15 mg/l InstTHM in Finished Water:* For the third example of a 100 mgd conventional treatment plant using a surface water source and having an average InstTHM concentration of 0.20 mg/l in the distribution system, a 50 percent decline in precursor concentration should be sufficient to bring this utility into compliance. Although they could be considered, approaches that produce modest effects on precursors—improving clarification, moving the point of chlorination, lowering the pH, and oxidation with potassium permanganate—probably would not be adequate.

Because the InstTHM concentration in the finished water is high, 0.15 mg/l, trihalomethane removal should be considered. An aeration system operating at 80 percent removal should be sufficient to reduce the InstTHM concentration to a value below the MCL.[4] Using data from one location, a diffused-air system at 20:1 air to water ratio or an aeration tower at the air to water ratio of 32:1, costing an additional 14¢/1,000 gal and 2.9¢/1,000 gal respectively, neglecting the cost of air treatment, might be adequate (**Table 1**).

(3B) *100 mgd Surface Water Utility - THM Concentration 2xMCL - 0.01 mg/l InstTHM in Finished Water:* Because the InstTHM concentration in the finished water is not high, the removal of trihalomethane precursors would be required. According to **Table 1**, either oxidation with ozone or chlorine dioxide or adsorption with powdered or granular activated carbon should be able to produce a 50 percent reduction in trihalomethane precursor concentration. The added costs for these four processes are: ozone, 7.9¢/1,000 gal; chlorine dioxide, 12¢/1,000 gal; PAC 11¢/1,000 gal; and GAC (sand

†Calculated in a manner similar to chlorine dioxide, but using the appropriate chemical.

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replacement, on-site reactivation) 11¢/1,000 gal, respectively. Beyond the differences in cost, each process has disadvantages; ozone produces other organic by-products as well as chlorite and chlorate, disposal of sludge may be a problem with powdered activated carbon, and granular activated carbon requires replacement or reactivation (Table 1). Decisions as to which processes to study should take all factors into account, but the least expensive treatment, ozone oxidation, would be the first choice.

(4) *100 mgd Surface Water Utility - THM Concentration 1.2xMCL:* The fourth example is a 100 mgd utility with a conventional treatment plant. Its surface water source and average InstTHM concentration of 0.12 mg/l in the distribution system would require a reduction of trihalomethane precursor concentration of only about 20 percent to bring the utility into compliance. Under these circumstances, techniques producing a modest removal of trihalomethane precursor, either improving clarification, moving the chlorination point, adjusting pH, or adding some oxidant, should allow the average InstTHM concentration in the distribution system to become acceptable at a very modest cost (Table 1).

With diligent disinfection as the final treatment step and proper surveillance of the distribution system, any of these processes can be used for trihalomethane control with the knowledge that water with an acceptable bacteriological quality will reach the consumer's tap. Of course, many other combinations of source water qualities, existing treatment processes, and treatment options can occur. The research report provides information concerning cost-effective treatment processes that can be considered by water utility personnel, design engineers and Primacy Agencies to successfully control the concentration of trihalomethanes in the nation's drinking water while maintaining high bacteriological water quality at the consumer's tap. ■

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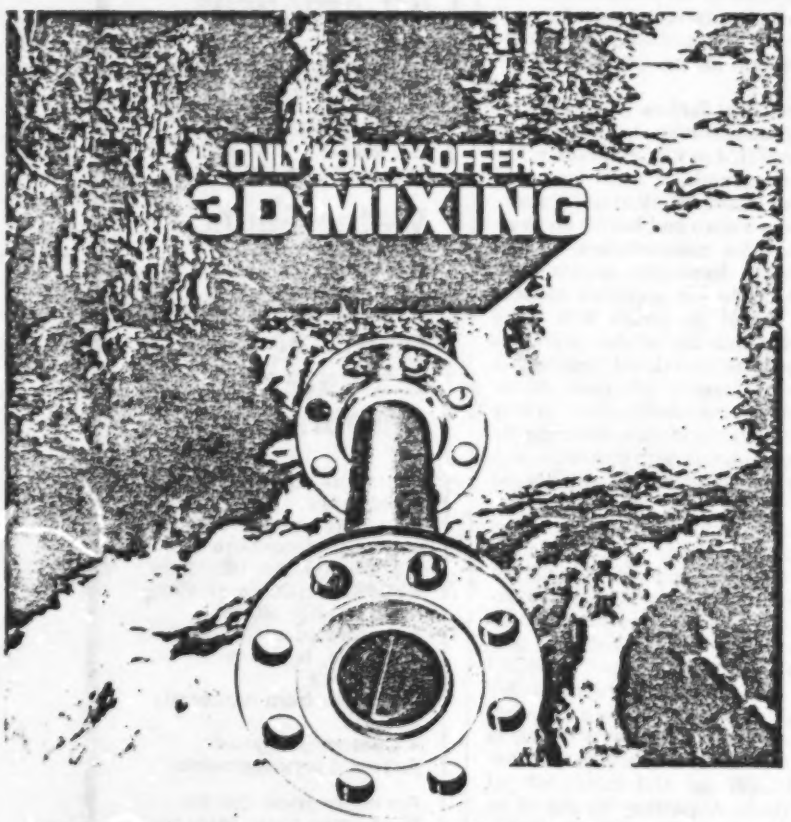

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